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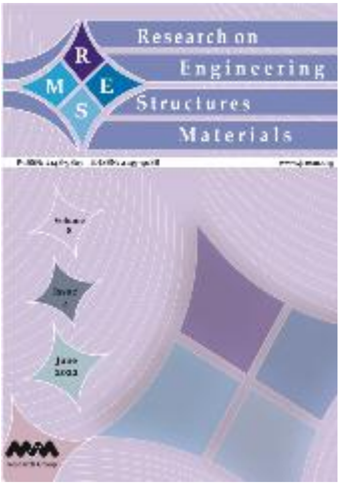

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Research Article

Nonlinear behaviour of reinforced concrete moment resisting frame with steel brace

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Abstract

In this study, the reinforced concrete moment-resisting concentrically braced frames (RC-MRCBFs) were used with V braced frames in new constructions. The core objective of this study is to understand the earthquake behavior of the RC-MRCBFs in steel V braced frames. The buildings were assumed to be located in Indian city and were designed by using Indian seismic code. The study also investigates the overstrength and ductility reduction factors, failure mapping and collapse mechanism to understand the seismic behavior of the capacity curve, maximum top story displacements and inter-story drift of the buildings. After studying the parametric study of the 4 to 16-story buildings with a nonlinear analysis tool it was observed that to get the effective braced frame with expected failure mechanism, ductility, the columns should be designed such that, it resists at least 50% base shear in a dual system. In conclusion, it was shown that a story yielding $\Delta y = 0.0024$ was the limiting value obtained for RC-MRCBFs when V shape steel bracings were used. It needs some improvements in the Indian seismic codes to develop adequate seismic behaviors of RC-MRCBFs for any steel braced frames.

1. Introduction

Construction of RC structures with a shear wall (SW) and steel structures with steel bracing are common practices in India. Moment resisting frame (MRF), SW and steel braced frames are used to resist the earthquake load and wind load to increase the seismic performance of the structure. It seemed that the earthquake load damaged the buildings and also sometimes collapse. It is because if the buildings do not resist the lateral seismic force, the buildings collapse or fail easily. To improve the lateral load capacity of the buildings, the generally designer used the shear wall in the RC structure. However, after successfully assigning the steel bracing in RC building as a retrofitting technique the result shows good seismic behaviors, the steel bracing is used as new construction as well. In the late 1980 and 1990, most of the research studies were focused on the retrofitting and strengthening of the RC frame with a different type of steel bracing. Both experimental and numerical studies are presented in existing buildings. Steel bracing improves seismic behaviors which are economic to use as compared to others. There are several types of steel bracing systems of which mainly concentrically braced and eccentrically braced frames are the most popular form of bracing. The concentric bracing frame consists of the bracing which is located in the plane of the frame and both the end of the bracing joined at the end of the frames. It provided the stability and stiffness of the building and reduce the lateral displacements effectively. In RC structure the concentric bracing is widely used because it is very easy to use and is also economically sound. Different configurations of bracings are used in a structure such as X bracing, V bracing, inverted V bracings (chevron),

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diagonal bracing, multi-X bracings and K bracings. Some other concentrically braced frames such as Buckling restrained braced (BRBs) frame, post-tensioning braced, lightweight BRBs, etc. are used in building construction as lateral load resisting systems. Bracings are also classified, based on the connection with beam and columns which is external bracing and internal bracings. When the bracing member is directly inserted into the enclosed space of the columns and beams, this is knowns as internal bracing and if the members of bracing are connected to the face of the beam and columns externally known as external bracings.

The retrofitting technique is generally used in the existing buildings to improve the strength and stiffness of the member or whole buildings [1]–[3]. It is necessary to retrofit the building. There are several methods of retrofitting such as column jacketing, providing shear wall, and damping. Some researchers found that applying the bracings in the RC structure, improves the seismic performance [4–6], and also is a cheap and effective method for restrengthening the buildings. Providing the steel bracing with a suitable slenderness ratio in RC frames shows the good seismic behaviors [7, 8]. Another researcher Bush TD et al. (1991) [9] implemented the experimental analysis of X braced non-ductile 2/3 scaling two bays frames. The experimentation was performed under the lateral loading and cyclic loadings and the researcher found that when 40-30% of base shear was carried by the columns and the remaining base shear in bracing. And researcher suggested that for best performance and result in the frame, it needed at least 50% base shear capacity in columns. Canales MD and R.B. de la (1992) [10] observed the telephone structure which was retrofitted by the steel bracing in 1992 Mexico. The paper concluded that when the steel bracing was applied in the existing RC buildings, it reduced the inter-story drift and displacement effectively under the earthquake loading. Rahimi, M.R. Maheri (2018), (2020) [11, 12] investigated the positive and negative effects of steel bracing in the RC frame when bracing is used in retrofitting techniques. The paper observed that the bracing improves the shear capacity, and ductility capacity, and also helps in the reduction of drift and top story displacement easily.

Many researchers have done very good research on the RC frame with steel bracing as lateral load resisting members [13–16]. The research gives very useful information about the braced behaviors in RC MRCBFs with different types of steel bracing [17–19]. It was observed that when the X and knee steel bracing was applied in the ductile RC frame, its strength (yielding capacity) and base shear capacity increased and also the maximum displacement of the building was decreased [20]. Godinez. E.A., and Tena-C. A. (2008) [21] performed the four to sixteen-story RC buildings with chevron shape bracing. The researcher considered the ductile RC-MRCBFs and analyzed with pushover analysis. The structures were considered the soft soil profile in Mexican cities with their won code and conduct. The paper observed the overstrength factor, yielding mechanism, drift curves and successfully designed the RC-MRCBFs when columns resist at least 50% of the total base shear strength. In the structures, the researchers also considered the three case studies such as the 25% base shear in bracing, 50% and 75% base shear in bracing, and remained base shear considered in moment resisting frames such as columns. Paper successfully designed the ductile RC-MRCBFs with an inverted V bracing frame when the minimum base shear force was resisted by the columns. The researcher also observed that structure only shows required suitable failure mechanisms such as weaker bracing, weak beam, and strong columns when the columns resist a minimum 50% base shear of the slender structure [22, 23]. For serviceability limits paper gives the acceptable drift limits 0.2% for new construction of the RC-MRCBFs buildings. Alike previous research by the same researchers they found that medium-rise building only gets required failure mechanisms such as the weaker bracing- weak beam and strong columns [23]. Researchers used the hysteretic energy dissipation device (HEDD) attached in inverted V braced configurations.

Researchers observed the structural behaviors when it was attached with steel bracing, HEDD, base shear and seismic weight ratio (V/W) considered as 1/10 [24]. Godínez, EA and Tena (2016) [25] studied the redundancy factor of the RC-MRCBFs having inverted V braced frames. Eskandari et al. (2017) [26] studied the four-story, eight-story, 12 stories and sixteen-story RC frame with diagonal bracing that was used and analyzed by the time history analysis and Nonlinear pushover analysis (NPA) for seismic analysis. The ground motion was selected so that they were far faults and near faults motions and studied the inter-story drift of the buildings. E. A. Godínez, A. Tena (2019) [27] in this paper, the researcher studied the RC-MRCBFs in a Mexican city and used Mexican codes. The structures have 4 to 20-story RC buildings with X bracings. K. Du, et al (2020) [28] studied the RC frame with the BRBs and observed the effect of forwarding directivity and fling step. The researchers used the diagonal, inverted chevron and chevron types of steel bracing in the RC frames.

In previous research of Godínez and Tena, (2010) and (2016) Godínez et al., 2012, [22], [23], [25], [29] they were focused on pushover and dynamic analysis of RC/MRCBFs using the chevron SB and applied MFDC-04 codes. Eskandari R. et al. (2017) [26] investigated the diagonal steel bracing in concrete frame structure and analysis based on the Iranian Seismic Design Code. K. Du, et al., (2020) [28] investigated the inverted V, diagonal, and V and observed the effect of forwarding directivity (FD) and fling-step (FS) on the RC structure having buckling-restrained braces (BRBs). E. A. Godínez and A. Tena (2019) [27] studied X steel bracing in MRCBFs by using MFDC-04. Except the K. Du, et al (2020) [28] other literature mainly focused on developing the guideline of the new design of RC braced frames. Therefore, the research on the moment-resisting frame with concentrically braced frames using V-shape steel braced with ductility property permits to completion of the research, which is commonly used in bracing arrangements in India and world.

In this paper the nonlinear lateral load behaver of low (4 story) to medium-rise (16 story) moment-resisting RC frames with a concentrically braced structure where steel V bracing (inverted chevron), situated high earthquake zone in India. The study focused on the Indian standard code and some international design codes. The study of key design parameters such as building capacities, strength and overstrength and ductility factors and story displacement corresponding to various states, failure mapping and plastic hinge formation in beams and columns are estimated. The study considers the provision, which is mentioned in IS 1896 (part 1) clauses 7.2.7 dual system, MR frames (columns) are designed to resist at least 25% designed base shear independently and suggested some findings based on the results obtained.

2. Methodology and Analysis

To design the ductile RC-MRCBFs, a capacity design methodology is used to get the excepted failure mechanism of a weaker brace-weak beam-strong column. There is a lack of general design guidelines for many international codes and IS codes to design ductile RC moment-resisting concentrically braced frames. The methodology proposed by Godínez and Tena, published in (2010), (2012), and (2019) [22, 23, 25] is known as the 'Conceptual capacity design' methodology which is used in this study. In a previous study, Godínez Domínguez and Tena-Colunga used this methodology in inverted V and X bracing, also R. Eskandari et al. (2017) [26] used the same method to design diagonal bracing in RC buildings. The bracing which is the main earthquake resisting member is designed as the weakest member in the RC-MRCBFs system. Other members Beam and columns are considered the strongest member. It is because of getting an expected failure mechanism for ductile design. There are four elements for earthquake resisting which are designed in such a way, to get the expected failure mechanism. These elements are bracings, beams, columns, and connection design of beam, columns, & bracing.

2.1. Lateral Shear Strength Contribution

According to IS 1896 (part 1) clauses 7.2.7 dual system, MR frames (columns) are designed to resist at least 25% designed base shear independently. In this study, at each building height, three different lateral shear strength values are assigned in the moment-resisting frame and bracing system. In RC-MRCBFs, lateral shear strength percentage resist by the columns are given below:

- In RC-MRCBFs up to 25% of shear force is provided in a MR frame (column). This is the almost minimum shear force balance in columns and which is less than the strength provided in the bracing system. However, this balance is allowed in IS code but some international codes do not allow for ductile design.
- Nearly up to 50% of shear force resist by the MR frame (column).
- Up to 75% of the shear force is provided in the moment-resisting frame (column).

Above three shear strength balances are used to know the seismic behavior of the RC-MRCBFs at the different shear values in their dual system in both structural systems and the height of the building [20, 22]. It also reviews the minimum strength requirement in the dual system, especially in V braced RC-MRCBFs according to the IS code for ductile designing.

2.2. Geometry and Design Parameters of the Buildings

12 RC-MRCBFs of V braced buildings are designed by using the Indian standards code. For seismic design IS 1896 part1 [30], reinforced concrete design IS156, IS800 for steel design, ductile design guideline IS 13920:2016 [31], IS 4923:1997, are used to achieve the required seismic behavior. The regular RC buildings with the concentrically braced frame using V-steel bracings are designed for the soft soil's condition, using response reduction factor R=4.5 [30]. Which is corresponding to a 5% damping ratio. The building models are four-story, eight-story, twelve-story, and sixteen-story regular RC-MRCBFs having 7m spans in each X and Y direction and 3.2 m story height. Outer RC frames consist of steel bracing which is used to resist earthquake loads. The plan and elevation view is given in Figure 1. RC-MRCBFs are designed using various lateral force ratios of base shear in columns/base shear in bracings. The H/L (slenderness ratio) mainly affects the seismic behavior of the building so different height ranges of buildings are studied carefully. The live load and dead load are considered as follows:

Live load = 5 kN/m^2 (business and office building)

Live load at roof level= 2 kN/m^2

Finishing dead load = 2.5 kN/m^2

The material property used in the RC and steel members for design are given in Table 1, where E_c and f_{ck} are the modulus of elasticity and compressive strength for concrete respectively, f_y is the yield strength for steel reinforcement bar used in RC structure, f_{ys} and E_s are the yield stress and modulus of elasticity of steel bracing respectively.

The design section of RC-MRCBFs changes along the height to reduce the strength and stiffness irregularities along with the height as much as possible. The sectional of columns and beams change their steel reinforcement or cross-section every four stories for eight, twelve, and sixteen-story buildings. The box cross-sectional of steel V-bracing changes its thickness every four stories for eight, twelve, and sixteen story frames, to get the design optimum as much as possible. The designed section of beam, columns and bracings are taken from the thesis (see Tables 2 to 5) [14].

Table 1. Material Properties

Building height	Concrete member properties			Steel member properties		
	f_{ck}, MPa	E_c, MPa	f_y, MPa	f_{ys}, MPa	E_s, MPa	μ
4 to 16-story models	25	$5000\sqrt{f_{ck}}$	415	250	210000	0.3

To design the RC MRCBFs, the following seismically design procedure was considered.

- Initially all design factors and modeling parts are determined.
- Calculate the design equivalent lateral force.
- Calculate the percentage of shear strength provided separately in the moment frame and steel bracing.
- Design the braces according to their lateral base shear contribution.
- Now design the beams and columns for their base shear contribution in frame structure and also consider the strong column weak beam principle.
- Check ta allowable inter-story drift limit and some of the steps are repeated to get the required design section.

Table 2. Detailing of 4 Story Buildings

Model	Story	Beams	Bracing	Columns Section
VF25D4	1-3	350X450	180X180X8	450X450
	4	300X350	180X180X5	350X350
VF50D4	1-3	350X450	113.5X113.5X6	500X500
	4	300X350	113.5X113.5X4.5	400X400
VF75D4	1-3	350X500	72X72X4.8	600X600
	4	300X400	72X72X4	500X500

Table 3. Detailing of 8 Story Buildings

Model	Story	Beams	Bracing	Columns Section
VF25D8	1-4	350X450	210X210X16	570X570
	5-8		210X210X12	400X400
VF50D8	1-4	400X500	180X180X6	600X600
	5-8		180X180X5	550X550
VF75D8	1-4	400X500	100X100X5	700X700
	5-8		100X100X4	650X650

To categorize the 12 models, a cryptogram is well-defined as VFpDn, where VF specifies V bracing frame, p known as shear strength percentage provided in columns, D represent the direction (X and Y axis) as shown in (Figure 1), and 'n' defines the number of floors. For example, VF25X4.

Table 4. Detailing of 12 Story Buildings

Model	Story	Beams	Bracing	Columns Section
VF25D12	1-4	400X500	300x300x22	650x650
	5-8	400X450	300x300x20	570x570
	9-12	375X450	300x300x18	500x500
VF50D12	1-4	400X500	200X200X8.5	675X675
	5-8	400X450	200X200X6.5	625X625
	9-12	375X450	200X200X5	550X550
VF75D12	1-4	400X500	113.5X113.5X6	780X780
	5-8	400X450	113.5X113.5X5.4	750X750
	9-12	375X450	113.5X113.5X4.8	725X725

Table 5. Detailing of 16 Story Buildings

Model	Story	Beams	Bracing	Columns Section
VF25D16	1-4	400X550	350X350X30	700X700
	5-8	400X500	350X350X28	650X650
	9-12	400X450	350X350X26	600X600
	13-16	400X450	350X350X24	575X575
VF50D16	1-4	400X550	200X200X14	750X750
	5-8	400X500	200X200X12	700X700
	9-12	400X450	200X200X10	650X650
	13-16	400X450	200X200X8	600X600
VF75D16	1-4	400X550	125X125X8	900X900
	5-8	400X500	125X125X6	875X875
	9-12	400X450	125X125X5	850X850
	13-16	400X450	125X125X4	825X825

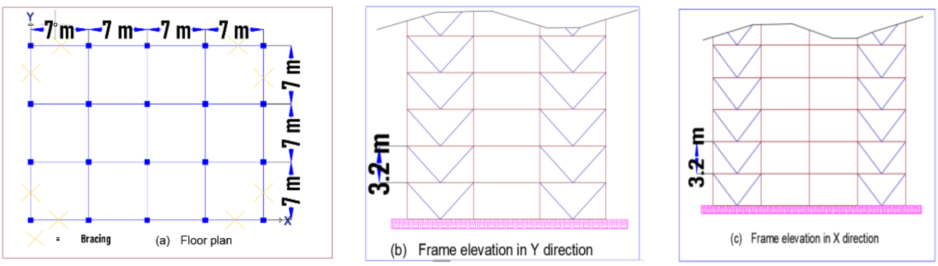


Fig. 1 Floor plan and elevation view in dual systems under study (all units are in meter (m))

3.1. Nonlinear Static Analysis

Mwafy and Elnashai (2001) [32] studied both nonlinear static and time history analysis of the RC building one of the conclusions is suggested that NPA is more appropriate for the low period that is low to medium-rise regular RC frame structure. A similar result also suggested by Goel RK, Chopra AK (2004) [33]; Chopra and Goel RK. (2002) [34]; Godínez & Tena (2010) [22] used NPA to study the behavior of 4 to 24 stories, RC-MRCBFs with chevron steel bracing. Eskandari et al. (2017) [26] conducted nonlinear static analyses for

4- to 16 stories in RC-braced, Eber Alberto Godínez et al. (2019) [27] in 4 to 20 stories RC, X braced frame. Nonlinear static analyses help to obtain the story and global shear, drift curve, yielding mapping, overstrength factor, ductility factor, peak story drift, and global ductility capacity. Uang CM (1991) [35] developed the design of the formula of response reductions factor (R) and displacement factor (Cd). And also studied the structural strength factor and structural ductility factor (Rμ).

Table 6. Characteristics of the Investigated Buildings

Model	Slenderness ratio H/L	Shear distribution		Time period (t)s	Model	Slenderness ratio H/L	Shear distribution		Time period (t)s
		Columns %	Bracing %				Columns %	Bracing %	
VF25X4	0.46	25	75	0.425	VF25X12	1.37	25	75	1.12
VF50X4	0.46	50	50	0.512	VF50X12	1.37	50	50	1.34
VF75X4	0.46	75	25	0.547	VF75X12	1.37	75	25	1.54
VF25Y4	0.61	25	75	0.426	VF25Y12	1.83	25	75	1.11
VF50Y4	0.61	50	50	0.514	VF50Y12	1.83	50	50	1.35
VF75Y4	0.61	75	25	0.552	VF75Y12	1.83	75	25	1.55
VF25X8	0.91	25	75	0.754	VF25X16	1.83	25	75	1.61
VF50X8	0.91	50	50	0.908	VF50X16	1.83	50	50	1.74
VF75X8	0.91	75	25	1.035	VF75X16	1.83	75	25	1.99
VF25Y8	1.22	25	75	0.752	VF25Y16	2.44	25	75	1.61
VF50Y8	1.22	50	50	0.914	VF50Y16	2.44	50	50	1.75
VF75Y8	1.22	75	25	1.047	VF75Y16	2.44	75	25	2.01

This paper used the NEHRP and the Uniform building code (1988) recommended provision. One of the conclusions of this paper is 'the structural overstrength factor which is governed by on structural redundancy, the story displacement or Inter story drift limitations, load combination, strain hardening, and other parameters'. 4- to 16 stories buildings were analyzed in ETABS 2018. To know the seismic behavior of the buildings, NPA is used. In beam and columns, flexural and shear hinges are provided and in bracing axial hinges are provided. Where the maximum lateral load and resultant moments are present, the flexural (M3) plastic hinges are assigned to each end of the beam and in columns, axial biaxial moment (P-M2-M3) plastic hinges are placed on each end. In the ETABs software, the hinge length is defined to obtain the inelastic performance by the integration of the plastic curvature and plastic strain. The hinge properties in the software are defined as a force-displacement or moment rotation way and assigned in the fixed location in the length of beam bracing or columns. The number of hinges and location of hinges is highly affecting the analysis time and behavior of the structure so assigning the hinges needs to be careful. In the ETABs, the hinges are defined the various way. Auto hinges property, user-defined hinges property, and program generated hinges properties are the way to provide the hinges in the ETABs software. Structures show different performance levels according to their structural and non-structural components. The capacity curve help to understand the performance level of the structures, different structural and non-structural members have their performance level under the loading. Figure 2. AB- linear range from the unloading state (A) to the yield state (B). B to C represents inelastic ranges CD indicates the rapid decrease in strength resistance and followed by a reduced resistance from D to E. some key points Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) are also considered. These points are generally found when dividing B-C into four parts as shown in Fig. 2, and represent IO, LS, and CP which are states of each hinge. At the Operational level in structure means, in the building, there is no major damage or crack in structural members. The structure has its original strength at this level. At the immediate occupancy level, the structural members and walls have some minor cracks observed. The structure has no any permeant drift and also has original strength. At the life safety level, the structure loses some original strength and stiffness. The structure shows some drift and the nonstructural members are under failure stages. The structure has large displacement and the failure of members is observed in the collapse prevention level.

The NPA is used to get the strength capacity of the building its limit state up to the failure strength. The lateral load is distributed along with the height with a predefined pattern vertically. The lateral load along with the height looks like an inverted triangular shape. The lateral load pushes the structure and the base shear is recorded for every push that is displacement and the graph is plotted. At the displacement where the buildings behave the in-elastically and known as the target point also known as the performance point. The analysis is completed when two things are observed one target point and another is the capacity curve. The analysis predicts potential weak areas.

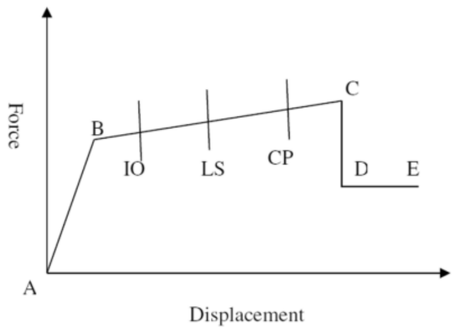


Fig. 2 Performance level for pushover analysis

3.1.1. Capacity Curve

The curve plotted between base shear and displacement known as a capacity curve which is obtained after pushover analysis is performed in each designed model. The curves are obtained from the 4 stories, 8 stories, 12 stories, and 16 story models as shown in Figs. 3 to 6. The curve represents the lateral shear strength in columns and bracing and is plotted to understand the behavior of each structure. Previous literature provided that the sum of each individual strength (columns and bracing) indicate the total lateral shear force for the RC-MRCBFs [20]. It is obtained that the base shear is increased as height and lateral force contribution in columns decrease. For the observation, the three (25%, 50%, 75%) cases of each story (4, 8, 12, 16) are put in the same graph. The x-axis and y-axis are separated and observed nonlinear behaviors.

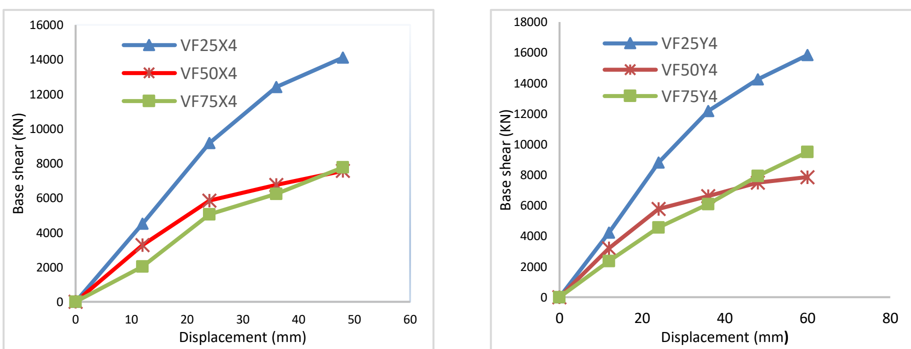


Fig. 3 Base shear vs displacement graphs for 4 story steel braced RC frame along both axes with different base shear in columns

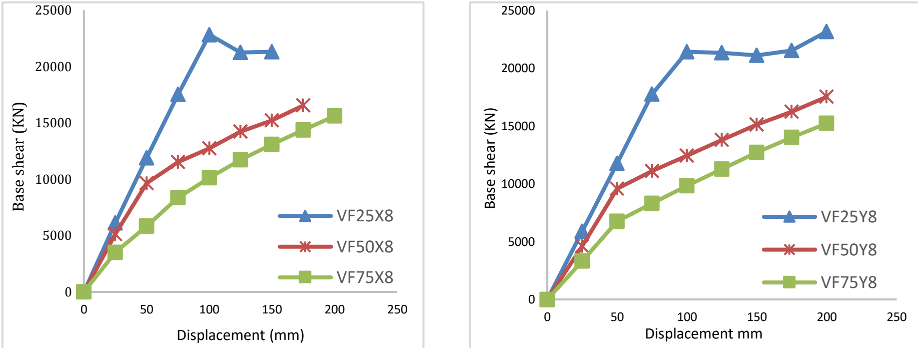


Fig. 4 Base shear vs displacement graphs for 8 story steel braced RC frame along both axes with different base shear in columns

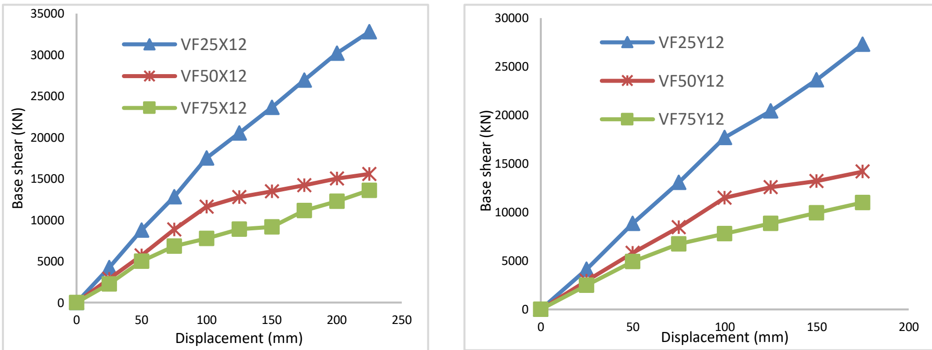


Fig. 5 Base shear vs displacement graphs for 12 story steel braced RC frame along both axes with different base shear in columns

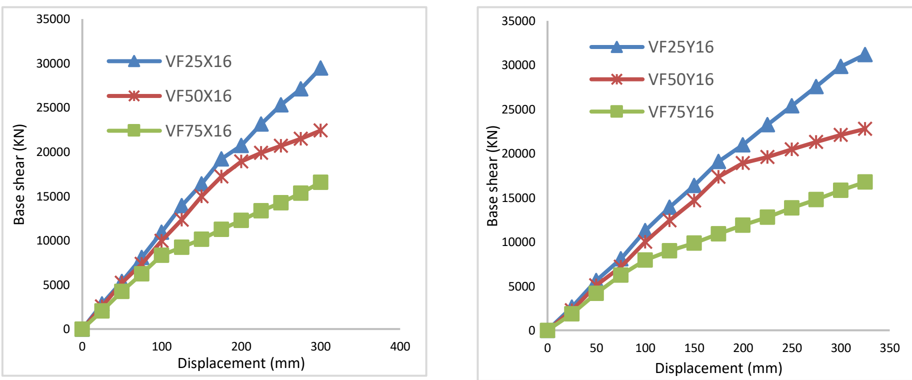


Fig. 6 Base shear vs displacement graphs for 16 story steel braced RC frame along both axes with different base shear in columns

When the base shear contribution in the bracings is increased the structural strength also increased. The 50% base shear contribution configurations have shown the uniform distribution of the energy decapitation capacity. Models VF25X4, VF25X8, VF25X12 and VF25X16 have the main line of defense is steel and these model have high strength. The models VF75X4, VF75X8, VF75X12 and VF75X16 have the main line of defense in the columns and have low shear strength. The steel bracing increased the strength of the structure and reduced the maximum top story displacement which is shown in Figures 3 to 6. Also observed is that the V bracing in the 4-story building shows irregular behaviors. It is because in the lower story the gravity load plays the main role in the structural response. While the base shear increases up to 25% in columns the seismic response is quite different. The first hinges are formed in the bracing then it may be in columns or beams. Hence it is observed, that higher contribution in the bracing should be avoided as possible in the new construction of the RC-MRCBFs. Also when the columns get a high lateral shear contribution (75% or more than 75%) the bracing loses its contribution importance. The bracing easily comes in fail and it does not resist the more seismic forces. To get the balance seismic behaviors and economic column sections, there should avoid a lower shear contribution in the bracing as well. From an economical point of view, the heavy cross-section of the columns and steel bracing should not be used in new constructions. However for the retrofitting, there is already the column sections are fixed, at that condition, may use the heavy cross-section of the steel. As a sectional area of the bracing increased the lateral shear resisting capacity also increased as shown in Figures 3 to 6.

3.1.2. Collapse Mechanism

The failure mapping shows the hinge formation in the structure at the final stage where the structure shows collapse behavior. The collapse mechanism study shows that the nonlinear behavior of the structures and energy dissipate capacity for input earthquake force. For the observation of the failure mechanisms, it helps to conclude the weaker brace-weak beam and strong-column collapse mechanisms can be obtained or not by the observation of the plastic hinge in the columns, beams, and bracing. It is observed that the percentage of the strength provided in the columns increases, the rotation demands decrease in columns and increased in a brace.

Failure mapping is the development of plastic hinges in the structural members (beam, column, and bracing) in a different stage in NPA. The plastic hinges in the bracing are divided into compression bracing hinges and tension bracing hinges. The yielding in steel bracing due to the compression force is also known as buckling failure. The maximum bracings are failing due to buckling failure.

In the observation of the graph and the development of the plastic hinges pattern, it is found that the models having 25% base shear contribution are the non-ductile models and the model having 50% and 75% base shear contributions in the columns are the ductile models. These models VF25 are the non-ductile failure and other models VF50, and VF75 have ductile failures. However, the Indian standard code allowed the 25% base shear in columns in the duel system structures. In the study of each model, it is found that only ductile models show the expected failure mechanism. In the models VF50 and VF75, only the first failure is seen in the steel bracing than the beam and last in the columns. Which followed the adequate failure pattern such as weaker bracing, weak beam and strong columns. This type of failure pattern not seen in the models when the model (VF25) contributes the 25% base shear in the columns. However, the first plastic hinges are formed in the steel bracing in all the models. It is also noticed that the failure mechanism in the VF25 models the unsuitable and irregular pattern of the development of the plastic hinges. In the models having 50% and 75% base shear contribution, the formation of plastic hinges is formed in a regular pattern.

In previous research in the inverted V bracing [22], diagonal [26] and X bracings [27], the same results are obtained in the V bracing RC frame as well. The result of this section is for getting a suitable failure mechanism, the shear stress contribution in the columns should be a minimum of 50% of the total lateral shear. Also in IS 1893:2016, a dual system for steel bracing in RC frame should be reviewed and consider the minimum 50% base shear contribution of the moment-resisting frame to get adequate failure and ductile buildings.

3.1.3. Ductility Reduction Factor and Ductility Capacity (μ)

Displacement capacity, ductility, and ductility ratio are the interrelated seismic response parameter. The ductility factor depends upon the story level and system. The ductility reduction factor ($R\mu$) is used for the calculation of the nonlinear seismic response of the buildings which is caused by the hysteretic energy. The term ductility reduction factor depends upon the damping, ductility, and the fundamental time period. Equations give the ductility reduction and ductility capacity respectively.

However, in this study to calculate the response ductility factor, Newmark and Hall (1982) [36] proposed equations are used (Eqs. 1 - 5). Newmark, Hall (1982) [36] proposed the essential study in ductility reduction factor. This method is widely accepted by other researchers for their study.

Periods (T) ≤ 0.03 sec:

$$R\mu = 1.0 \tag{1}$$

T: 0.03 < 0.12 sec:

$$\mathrm{R}\mu = 1 + \frac{(T - 0.03).(\sqrt{(2.\mu - 1)} - 1)}{0.09} \tag{2}$$

T: 0.12 ≤ T ≤ 0.5 sec:

$$\mathrm{R}\mu = \sqrt{(2.\mu - 1)} \tag{3}$$

T: 0.5< T<1.0 sec

$$\mathrm{R}\mu = \sqrt{(2.\mu - 1)} + 2(T - 0.5).\left(\mu - \sqrt{(2.\mu - 1)}\right) \tag{4}$$

T ≥ 1.0 sec:

$$R\mu = \mu \tag{5}$$

Where T is the natural time of the buildings (also known as the fundamental time period). V_0 and V_d are the maximum base shear and design base shear respectively. Δ_m and Δ_y are the maximum displacements and first yield displacement respectively from the pushover curve. μ, R_μ, R_s, and R are the ductility ratio ($\mu = \Delta_m / \Delta_y$), ductility reduction factors, overstrength factors ($R_s = V_o/V_d$), and response modification factors ($R = R_\mu X R_s$) respectively. In this method, it is assumed that redundant factors are taken 1.

It is observed that the ductility ratio (μ) is greater than 3 or 4 which is generally assumed as a have a high deformation demand. The models VF50 and VF75 have a value greater than 3, which shows the ductile behaviors of the buildings. It is observed in shown in Figure 7 that when the H/L value increased, the ductility ratio decreased. Same results also observed in the paper E.A. Godínez, A. Tena (2010) [22] for inverted V braced RC frame and Godínez Domínguez et al. (2019) [27] for X steel braced RC frame for the relationship between the μ and H/L. For 4 to 16 story buildings, the ductility ratio decreases when the base shear contributions by the columns increase. Thus observation suggested that for suitable ductile and failure mechanisms of the buildings, minimum of 50% lateral base shear contribution by the columns should be used in dual systems. As shown in Figure 8

(a) for the monotonic pushover load, the ductility reduction factors increase as the FTP of the buildings increases. In the other words, for the short time period buildings, the ductility reduction factors are low for V-shaped steel bracing RC frame buildings. It is also noted that greater shear strength contributions in the columns have higher ductility reduction factors. However, in the paper, Godínez and Tena (2010) [22] for inverted V braced RC frame the result is opposite as compared to the V braced RC frame results. In this paper the ductility reduction factors increased as a FTP of the buildings decreased. When the H/L ratio increases the ductility reduction factors also increase as shown in Figure 8 (b).

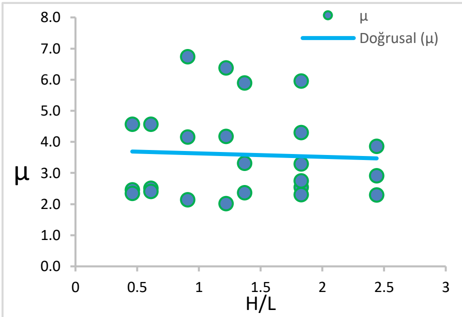
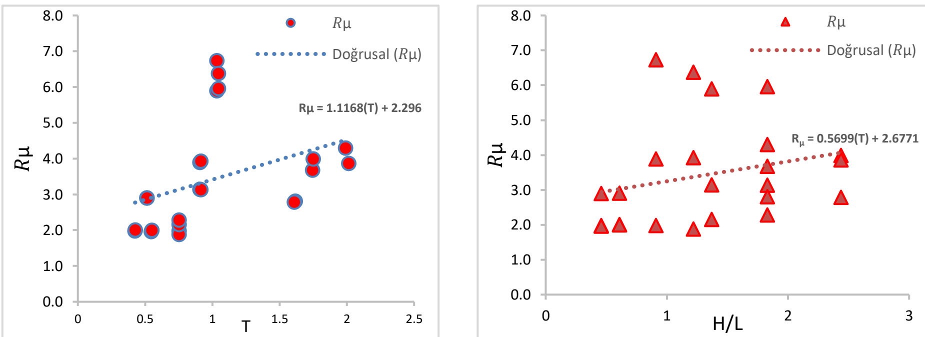


Fig. 7 Relationship between the ductility ratio and slenderness ratio



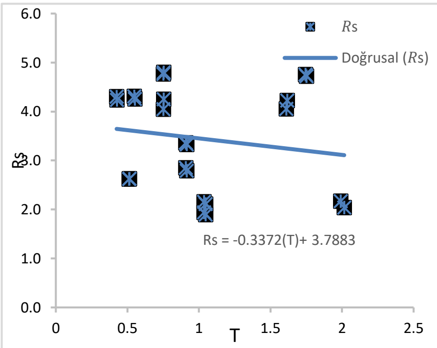
(a) Relation with natural time period (b) Relation with H/L

Fig. 8 Relationship of the ductility reduction factors with fundamental time and slenderness ratio

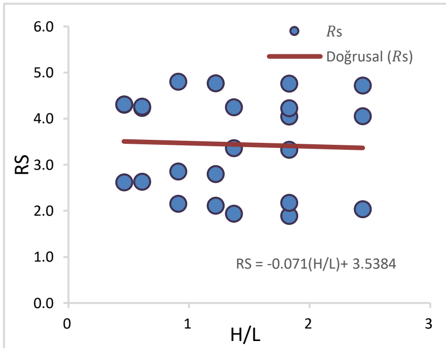
3.1.4. Strength Factor and Response Modification Factors

It is the ratio of the maximum base shear and design base shear which are obtained by the NPA. The individual members of the buildings have over reserved strength, it's due to the redundancy of the structural members. Many things affect the strength factors, such as actual and practical construction differences actual strength of the materials, seismic zone, and gravity loads. Generally, the actual strength of the structures is high as compared to the design strength. It's the main reduction factor used in response modification factors (R). It is observed that the strength contribution of the columns increases, the Rs factors decrease ways. The observation is similar to the previous study in paper E.A. Godínez and A. Tena (2010) [22] for inverted V braced RC frame. However, the result is the opposite for the X-bracing RC frame in the paper Godínez et al. (2019) [27]. The buildings with increasing the natural time period (4 stories to 16 stories) have lower the overstrength factors as shown in Figure 9 (a). The result is also similar to the Godínez and Tena (2010)

[22]. Figure 9 (a) is the relationship between the FTP of the structures and overstrength factors which help to understand the behaviors of the Rs factors with time versions. To know the geometrical property related to the Rs factors the second plot Figure 9 (b) used, which shows the relation to the Rs and slenderness ratio. The slenderness ratio of each model lies between 0.46 and 2.44 ($0.46 \leqslant H/L \leqslant 2.44$). It is shown in Figure 9 b, the strength factors are decreased as the aspect ratio (H/L) increases. When the H/L ratio has a larger value the Rs factors have a lesser value. The linear relationship is obtained as shown in (plot H/L vs Rs) Figure 9 (b). Response modification factors (R) are the function of the ductility reduction factors, overstrength factors, and redundancy factors. The product of the Rs, $R\mu$, and redundancy factors (=1) gives the R. In the IS 1893:2016 the response modification factor is named as 'response reduction factor'. The response reduction factors in the Indian code seem incomplete such as the code does not tells as R factors for RC frame with concentrically braced steel bracing. It just tells as a concentrically braced frame with R factors 4.5. In the observation, it is noticed that the increases in the response modification factors as increasing the aspect ratio (H/L) as shown in Figure 10. It means increasing the story (4-16 story) also found increases in the R factors. The linear relationship observed between the R factors vs H/L ratio is shown in Figure 10.



(a) Graph between Rs and T



(b) Graph between Rs and H/L

Fig. 9 Overstrength factors having a relationship with natural period and slenderness

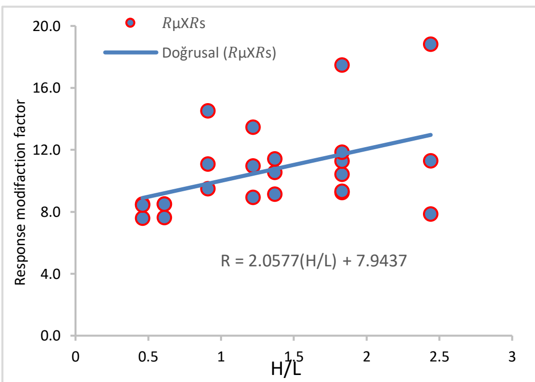


Fig. 10 Relationship between the response modification factors and slenderness ratio

3.1.5. Maximum Drift at a Yield Level

It is observed that the story drift at the yielding level is lesser than the 0.004 which is proposed by the code. The 0.004 drift is generally known as the drift limit at the service level and this value is generally proposed for the simply moment-resisting frame. This is because the maximum drift value for RC-MRCBFs is lesser than the service limit value. Yielding drift is computed by using the pushover curve with a bilinear idealized curve. It is observed that as the height of the building increases the maximum yield drift also increases (Figure 11). Figure 11, which is the relation between the yielding drift and slenderness ratio. The yielding values are only considered for the 50% and 75% of the base shear contribution of the columns. It is because the 25% base shear contribution by the columns is quite unfavorable for design and these models (VF25) show the unexpected failure mechanism. It is also noticed that the maximum yield drift is shown in the middle height of the structures. The average of each maximum drift at the yield level is 0.0024 which is nearly similar to the previously calculated value of 0.002 in [22] for inverted V braced RC-MRCBFs.

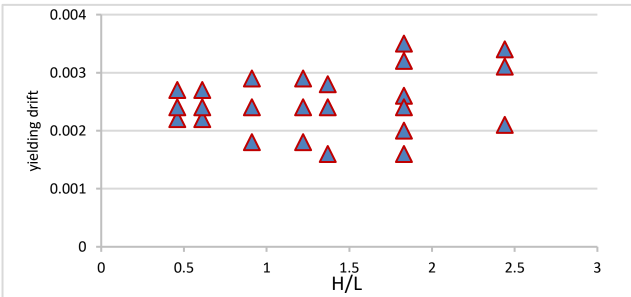


Fig. 11 Relationship between the maximum yielding drift and slenderness ratio for the VF50 & VF75 models

4. Conclusions

The nonlinear analysis was performed in 4 to 16-story buildings with three cases (25%, 50% and 75% base shear contributed by the columns) to study the nonlinear seismic behaviors of the structures. The RC-MRCBFs with steel V bracing structures were assumed to locate in the soft soil in India with high seismic zone factors. In this study the "moment resisting frames are designed to resist independently at least 25 percent of the design base shear" was considered for the design of the RC-MRCBFs. Based on the result obtained the conclusion are made as follows:

- Providing the steel V bracings in RC frames improves the seismic performances such as stiffness, strength and ductility of the structures effectively.
- The results shows that when the columns are designed to resist 25% base shear in dual systems, it is not possible to design columns as a strongest member. Many international codes suggested that columns are designed to resist minimum 50% base shear. So the Indian standard code should be revised. IS 1893:2016, a dual system for steel bracing in RC frame should be reviewed and consider the minimum 50% base shear contribution of the moment-resisting frame to get adequate failure and ductile buildings.
- The study observed that in the RC-MRCBFs for V shape steel bracings system when the moment-resisting system (columns) resists at least 50% base shear, those frames show the strong-column, weak-beam and weaker-bracing system. It

also improves the ductility and capacity of the structures for 4 story to 16 story structures.

- As increasing the strength of columns that is when base shear contributions of the columns increase, the capacity of the structures is decreased. However, when columns resist less than 25% base shear, the steel bracings are the main line of defense, which means, the structures do not show expected failure mechanism and non-ductile behaviors.
- Higher the shear force contributions in columns, the higher the ductility reduction factors, and the lower the ductility ratio obtained.
- When the aspect ratio (H/L) ratio increases, the ductility ratio of the structures decreases. It is also observed that the overstrength factors decrease as the aspect ratio (H/L) decreases. In the observation, it is noticed that the increase in the response modification factors as increasing the aspect ratio (H/L).
- When the base shear capacity increases in the columns, it decreases the overstrength factors and increases the response modification factors.
- The study shows that the story yielding $\Delta y = 0.0024$ which is the limiting value obtained for RC-MRCBFs when V shape steel bracings is used. This value is obtained for the service limit state.
- As increasing the height of the structures (in this study 4 to 16 stories), to get ductile and expected failure mechanism (weaker bracing, weak beam and strongest columns), it is ensured that to avoid the formations of plastic hinges at the lower stories columns end, it is done by the increasing the base shear capacity contributions in the columns to resist the lateral load.

This research is mainly focused on the regular buildings with 4 to 16 story buildings. The study is limited to nonlinear static analysis (pushover analysis) of up to 16 story RC buildings with V braced frame and a future study is needed to study the tall buildings with steel bracing with a suitable design methodology. The future research is needed to insure and to observe the effectiveness the design of RC-MRCBFs by using the nonlinear time history analysis of the models with different acceleration record. Further study is needed in the field of irregular buildings with different steel bracing with different shear contributions in the columns to understand the failure pattern of the structures.

References

[1] Maheri MR, Sahebi A. Use of steel bracing in reinforced concrete frames. Eng Struct, vol. 19, 1997. https://doi.org/10.1016/S0141-0296(97)00041-2

[2] Yoo JH, Roeder CW, Lehman DE. Simulated behavior of multi-story X-braced frames. Eng. Struct., vol. 31, 2009. https://doi.org/10.1016/j.engstruct.2008.07.019

[3] Yeom HJ, Yoo J.-. H. Analytical investigation on seismic behavior of inverted V-braced frames. Int. J. Steel Struct., vol. 18, 2018. https://doi.org/10.1007/s13296-018-0315-4

[4] Pincheira JA, Jirsa JO. Seismic Response of RC Frames Retrofitted with Steel Braces or Walls. J. Struct. Eng., vol. 121, pp. 1225-1235, 1995. https://doi.org/10.1061/(ASCE)0733-9445(1995)121:8(1225)

[5] Pincheira JA. Design strategies for the seismic retrofit of reinforced concrete frames. Earthquake Spectra, vol. 9, no. 4. pp. 817-842, 1993. https://doi.org/10.1193/1.1585742

[6] Badoux BM, Jirsa JO. Steel Bracing of RC Frames for Seismic Retrofitting. J. Struct. Eng., vol. 116, no. 1, pp. 55-74, 1990. https://doi.org/10.1061/(ASCE)0733-9445(1990)116:1(55)

[7] Osman A, Rashed A, El-Kady M. SEISMIC RESPONSE OF R.C. FRAMES WITH CONCENTRIC STEEL BRACING. in Proceedings of the 8th U.S. National Conference on Earthquake Engineering, 2006, pp. 18-22.

[8] Said A, Nehdi M. Rehabilitation of RC frame joints using local steel bracing. Struct. Infrastruct. Eng., vol. 4, no. 6, pp. 431-447, 2008. https://doi.org/10.1080/15732470600822033
[9] Bush TD, Jones EA, Jirsa JO. Behavior of RC Frame Strengthened Using Structural Steel Bracing. J. Struct. Eng., vol. 117, no. 4, pp. 1115-1126, 1991. https://doi.org/10.1061/(ASCE)0733-9445(1991)117:4(1115)
[10] Canales M, de la Vega RB. Retrofitting techniques used in telephone buildings in Mexico. in Earthquake Engineering, Tenth World Conference, 1992, pp. 5143-5147.
[11] Rahimi A, Maheri MR. The effects of retrofitting RC frames by X-bracing on the seismic performance of columns. Eng. Struct., vol. 173, no. August 2017, pp. 813-830, 2018. https://doi.org/10.1016/j.engstruct.2018.07.003
[12] Rahimi A, Maheri MR. The effects of steel X-brace retrofitting of RC frames on the seismic performance of frames and their elements. Eng. Struct., vol. 206, no. December 2019, 2020. https://doi.org/10.1016/j.engstruct.2019.110149
[13] Mahmoudi M, Zaree M. Evaluating response modification factors of concentrically braced steel frames. J. Constr. Steel Res., vol. 66, no. 10, pp. 1196-1204, 2010. https://doi.org/10.1016/j.jcsr.2010.04.004
[14] Birendra Kumar Bohara (2021). Nonlinear Behavior of Moment Resisting Reinforced Concrete with Steel Braced Frame under Lateral Loading. Mtech in Sharda University, 2021.
[15] Bohara BK. Ductility, R, and Overstrength Factors for V Braced Reinforced Concrete Buildings. Int. J. Struct. Constr. Eng., vol. 16, no. 3, pp. 101-105, 2022.
[16] Bohara BK, Ganaie KH, and Saha P. Effect of position of steel bracing in L-shape reinforced concrete buildings under lateral loading. Res. Eng. Struct. Mater., vol. 8, no. 1, pp. 155-177, 2022. https://doi.org/10.17515/resm2021.295st0519
[17] Ganaie KH, Bohara BK, Saha P. EFFECTS OF INVERTED V BRACING IN FOUR-STORY IRREGULAR RC. Int. Res. J. Mod. Eng. Technol. Sci., vol. 03, no. 04, pp. 2346-2351, 2021, [Online]. Available: www.irjmets.com.
[18] B. K. Bohara. Seismic Response of Hill Side Step-back RC Framed Buildings with Shear Wall and Bracing System. Int. J. Struct. Constr. Eng., vol. 15, no. 4, pp. 204-210, 2021.
[19] Bohara BK, Ganaie KH, and Saha P. Seismic Analysis of Retrofitting of RC Regular Frame with V-Braced Frame. J. Eng. Technol. Plan., vol. 2, no. 1, pp. 55-63, 2021, doi: 10.3126/joetp.v2i1.39229. https://doi.org/10.3126/joetp.v2i1.39229
[20] Maheri MR, Kousari R, Razazan M. Pushover tests on steel X-braced and knee-braced RC frames. Eng. Struct., vol. 25, no. 13, pp. 1697-1705, 2003. https://doi.org/10.1016/S0141-0296(03)00150-0
[21] Godínez-Domínguez EA, Tena-Colunga A. Behavior of moment resisting reinforced concrete concentric braced frames (RC-MRCBFS) in seismic zones. 14th World Conf. Earthq. Eng., pp. 12-17, Paper No. 05-03-0059, 2008.
[22] Godínez-Domínguez EA, Tena-Colunga A. Nonlinear behavior of code-designed reinforced concrete concentric braced frames under lateral loading. Eng. Struct., vol. 32, no. 4, pp. 944-963, 2010. https://doi.org/10.1016/j.engstruct.2009.12.020
[23] Godínez-Domínguez EA, Tena-Colunga A, and Pérez-Rocha LE. Case studies on the seismic behavior of reinforced concrete chevron braced framed buildings. Eng. Struct., vol. 45, pp. 78-103, 2012. https://doi.org/10.1016/j.engstruct.2012.05.005
[24] Tena-Colunga A, Nangullasmú-Hernández HJ. Assessment of seismic design parameters of moment resisting RC braced frames with metallic fuses. Eng. Struct., vol. 95, pp. 138-153, 2015. https://doi.org/10.1016/j.engstruct.2015.03.062
[25] Godínez-Domínguez EA, Tena-Colunga A. Redundancy factors for the seismic design of ductile reinforced concrete chevron braced frames. Lat. Am. J. Solids Struct., vol. 13, no. 11, pp. 2088-2112, 2016. https://doi.org/10.1590/1679-78252827

[26] Eskandari R, Vafaei D, Vafaei J, and Shemshadian ME. Nonlinear static and dynamic behavior of reinforced concrete steel-braced frames. Earthq. Struct., vol. 12, no. 2, pp. 191-200, 2017. https://doi.org/10.12989/eas.2017.12.2.191
[27] Godínez-Domínguez EA and Tena-Colunga A. Behavior of ductile steel X-braced RC frames in seismic zones. Earthq. Eng. Eng. Vib., vol. 18, no. 4, pp. 845-869, 2019. https://doi.org/10.1007/s11803-019-0539-0
[28] Du K., Cheng F., Bai J., Jin S. Seismic performance quantification of buckling-restrained braced RC frame structures under near-fault ground motions. Eng. Struct., vol. 211, no. December 2019, 2020. https://doi.org/10.1016/j.engstruct.2020.110447
[29] Godínez-Domínguez EA, Tena-Colunga A, Pérez-Rocha LE. Seismic behavior of chevron-braced RC framed buildings. in 15th World Conference on Earthquake Engineering, 2012, p. Paper No. 2813.
[30] IS 1893. Part 1. Indian Standard Criteria for Earthquake Resistant Design of Structures: General Provisions and Buildings. New Delhi: Bureau of Indian Standards, 2016.
[31] Bureau of Indian Standards, IS 13920. Ductile detailing of reinforced concrete structure subjected to seismic forces-Code of Practice. (1993).
[32] Mwafy AM, Elnashai AS. Static pushover versus dynamic collapse analysis of RC buildings. Eng. Struct., vol. 23, no. 5, pp. 407-424, 2001. https://doi.org/10.1016/S0141-0296(00)00068-7
[33] Goel RK and Chopra A. Evaluation of modal and FEMA pushover analyses: SAC Buildings. Earthq Spectra, vol. 20, no. 1, pp. 225-254, 2004. https://doi.org/10.1193/1.1646390
[34] Chopra AK, Goel RK. A modal pushover analysis procedure for estimating seismic demands for buildings. Earthq. Eng. Struct. Dyn., vol. 31, no. 3, pp. 561-582, 2002. https://doi.org/10.1002/eqe.144
[35] CM. U Establishing R (or Rw) and Cd factor for building seismic provision. J. Struct. Eng., vol. 117, no. 1, pp. 19-28, 1991. https://doi.org/10.1061/(ASCE)0733-9445(1991)117:1(19)
[36] Newmark N.M., Hall W.J. Earthquake spectra and design. Oakland: Earthquake Engineering Research Institute (EERI), 1982.